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13. ABSTRACT (Maximum 200 words)  We have studied quantum coherence and control in solid-state qubits, mostly in superconductors. We have outlined several strategies to obtain high-fidelity quantum logic gates in the presence of decoherence. We have studied realistic, structured environments to qubits, including environments with resonances, slow noise, and non-Markovian effects. In all cases, we have formulated strategies how to master and engineer the decoherence properties. We have analyzed examples from superconducting charge and flux qubits as well as quantum dots.				
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Enclosure 1

## Final report on contract DAAD-43384-PH-QC “Realistic theory of solid-state qubits”

This report covers the full period of the program, which included a one year no-cost extension. The funding was used for several people and connected to German funding. This way, we have been able to obtain a significant number of results. We would like to thank ARO to put this type of confidence in us as foreigners and as a junior group, and for the flexibility granted with the extension to make the money go a long way.

### **Statement of the problem studied**

Realistic modeling of decoherence and control in superconducting qubits

- i) decoherence in realistic environments
- ii) design rules for control and readout
- iii) proposal of optimized designs
- iv) study interplay of driving and dissipation
- v) decoherence during 2-qubit gate operation
- vi) transfer of knowledge to quantum dot charge qubits

### **Summary of the main results**

- i) decoherence in realistic environments

In the spin-boson model, the properties of the oscillator bath are fully characterized by the spectral density of oscillators  $J(\omega)$ . We studied the case when this function is of Breit-Wigner shape and has a sharp peak at a frequency  $\Omega$  with width  $\Gamma \ll \Omega$ . These environments are encountered in qubit detection, see section ii). We used a number of approaches such as the weak-coupling Bloch-Redfield equation, the non-interacting blip approximation (NIBA) and the flow-equation renormalization scheme. We showed, that if  $\Omega$  is much larger than the qubit energy scales, the dynamics corresponds to an Ohmic spin-boson model with a strongly reduced tunnel splitting. We also showed that the direction of the scaling of the tunnel splitting changes sign when the bare splitting crosses  $\Omega$ . We found good agreement between our analytical approximations and numerical results. We illuminated how and why different approaches to the model account for these features and discuss the interpretation of this model in the context of an application to quantum computation and read-out.

We studied a Josephson junction (JJ) in the regime of incoherent Cooper-pair tunneling, capacitively coupled to a nonequilibrium noise source. The current-voltage (I-V) characteristics of the JJ are sensitive to the excess voltage fluctuations in the source, and can thus be used for wideband noise detection. Under weak driving, the odd part of the I-V can be related to the second cumulant of noise, whereas the even part is due to the third cumulant. After calibration, one can measure the Fano factors for the noise source, and get information about the frequency dependence of the noise. This characterizes backaction of strongly coupled detectors.

We showed that single electron tunneling devices such as the Cooper-pair box or double quantum dot can be sensitive to the zero-point fluctuation of a single trapping center

hybridized with a Fermi sea. If the trap energy level is close to the Fermi sea and has linewidth  $\gamma > k_B T$ , its noise spectrum has an Ohmic Johnson-Nyquist form, whereas for  $\gamma < k_B T$  the noise has a Lorentzian form expected from the semiclassical limit. Trap levels above the Fermi level are shown to lead to steps in the noise spectrum that can be used to probe their energetics, allowing the identification of individual trapping centers coupled to the device.

The loss of coherence of quantum oscillations is of fundamental interest as well as of practical importance in quantum computing. In solid-state experiments the oscillations show, next to the usual exponential decay on time scales  $T_1$  and  $T_2$ , an overall loss of amplitude. We solve the spin-Boson model exactly in the pure dephasing point as well as approximately by perturbation theory in the qubit energy, for a large class of initial conditions, circumventing the familiar Born and Markov approximations. A loss of visibility occurs in the form of a fast initial drop for factorized initial conditions and an overall reduction for equilibrium initial conditions. This is compatible with long  $T_2$  for environments with real or pseudo-gaps. This result is explained by bandwidth effects in quantum noise as well as in terms of higher-order phase-breaking processes. For several experiments, such gapped environments are identified.

## ii) design rules for control and readout

We discussed the relaxation and dephasing rates that result from the control and the measurement setup itself in experiments on Josephson persistent-current qubits. For control and measurement of the qubit state, the qubit is inductively coupled to electromagnetic circuitry. This system can be mapped on the spin-boson model, and how the spectral density of the bosonic bath can be derived from the electromagnetic impedance that is coupled to the qubit. Part of the electromagnetic environment is a measurement apparatus (DC-SQUID), that is permanently coupled to the single quantum system that is studied. Since there is an obvious conflict between long coherence times and an efficient measurement scheme, the measurement process is analyzed in detail for different measurement schemes. The coupling of the measurement apparatus to the qubit can be controlled in situ. Parameters that can be realized in experiments today are used for a quantitative evaluation, and it is shown that the relaxation and dephasing rates that are induced by the measurement setup can be made low enough for a time-resolved study of the quantum dynamics of Josephson persistent-current qubits. Our results can be generalized as engineering rules for the read-out of related qubit systems.

A measurement on a macroscopic quantum system does in general not lead to a projection of the wavefunction in the basis of the detector as predicted by von-Neumann's postulate. Hence, it is a question of fundamental interest, how the preferred basis onto which the state is projected is selected out of the macroscopic Hilbert space of the system. Detector-dominated von-Neumann measurements are also desirable for both quantum computation and verification of quantum mechanics on a macroscopic scale. The connection of these questions to the predictions of the spin-boson model is outlined. I have proposed a measurement strategy, which uses the entanglement of the qubit with a weakly damped harmonic oscillator. The degree of entanglement controls the degree of renormalization of the qubit and identify, that this is equivalent to the degree to which the

measurement is detector-dominated. This measurement very rapidly decoheres the initial state, but the thermalization is slow. The implementation in Josephson quantum bits is described. This strategy also has practical advantages for the experimental implementation.

Recent experiments on superconducting flux qubits, consisting of a superconducting loop interrupted by Josephson junctions, have demonstrated quantum coherence between two different quantum states. The state of the qubit is measured with a superconducting quantum interference device (SQUID). Such measurements require the SQUID to have high resolution while exerting minimal backaction on the qubit. By designing shunts across the SQUID junctions appropriately, one can improve the measurement resolution without increasing the backaction significantly. Using a path-integral approach to analyze the Caldeira-Leggett model, we calculated the narrowing of the distribution of the switching events from the zero-voltage state of the SQUID for arbitrary shunt admittances, focusing on shunts consisting of a capacitance  $C_s$  and resistance  $R_s$  in series. To test this model, the Clarke group has fabricated a dc SQUID in which each junction is shunted with a thin-film interdigitated capacitor in series with a resistor, and measured the switching distribution as a function of temperature and applied magnetic flux. After accounting for the damping due to the SQUID leads, we found good agreement between the measured escape rates and the predictions of our model. We analyze the backaction of a shunted symmetric SQUID on a flux qubit. For the given parameters of our SQUID and realistic parameters for a flux qubit, at the degeneracy point we find a relaxation time of  $113 \text{ } \mu\text{s}$ , which limits the decoherence time to  $226 \text{ } \mu\text{s}$ . Based on our analysis of the escape process, we determine that a SQUID with purely capacitive shunts should have narrow switching distributions and no dissipation.

We presented a superconducting circuit consisting of a flux qubit and a single-charge transistor serving as a detector. As flux and charge are conjugate, the transistor can detect states of the qubit close to the flux degeneracy point, when the eigenstates are quantum superpositions of fluxes. The coupling has a flip-flop symmetry conserving the total number of excitations, and so the measurement outcome results in the absence or presence of an incoherent tunneling cycle. Evaluating the performance of a practical device we showed that it is an attractive tool for measuring at the degeneracy point.

### iii) proposal of optimized designs

Superconducting flux qubits are a promising candidate for solid-state quantum computation. One of the reasons is that implementing a controlled coupling between the qubits appears to be relatively easy, if one uses tunable Josephson junctions. We evaluated possible coupling strengths and show, how much extra decoherence is induced by the subgap conductance of a tunable junction. In the light of these results, we evaluated several options of using intrinsically shunted junctions and show that based on available technology, Josephson field effect transistors and high- $T_c$  junctions used as pi-shifters would be a good option, whereas the use of magnetic junctions as pi-shifters severely limits quantum coherence.

We proposed a scheme to implement variable coupling between two flux qubits using the

screening current response of a dc Superconducting QUantum Interference Device (SQUID). The coupling strength is adjusted by the current bias applied to the SQUID and can be varied continuously from positive to negative values, allowing cancellation of the direct mutual inductance between the qubits. We showed that this variable coupling scheme permits efficient realization of universal quantum logic. The same SQUID can be used to determine the flux states of the qubits.

#### iv) study interplay of driving and dissipation

We studied a realistic model for driven qubits using the numerical solution of the Bloch-Redfield equation as well as analytical approximations using a high-frequency scheme. Unlike in idealized rotating-wave models suitable for NMR or quantum optics, we studied a driving term which neither is orthogonal to the static term nor leaves the adiabatic energy value constant. We investigated the underlying dynamics and the spectroscopy peaks obtained in recent experiments. This system exhibits nonlinear driving effects. We studied the width of spectroscopy peaks and show, how a full analysis of the parameters of the system can be performed by comparing the first and second resonance. We outlined the limitations of the NMR linewidth formula at low temperature and show, that spectroscopic peaks experience a strong shift which goes much beyond the Bloch-Siegert shift of the eigenfrequency.

With the growing efforts in isolating solid-state qubits from external decoherence sources, the origins of noise inherent to the material start to play a relevant role. One representative example are charged impurities in the device material or substrate, which typically produce telegraph noise and can hence be modelled as bistable fluctuators. In order to demonstrate the possibility of the active suppression of the disturbance from a single fluctuator, we theoretically implement an elementary bang-bang control protocol. We simulated the random walk of the qubit state on the Bloch sphere with and without bang-bang compensation by means of the stochastic Schroedinger equation and compare it with an analytical saddle point solution of the corresponding Langevin equation in the long-time limit. We find that the deviation with respect to the noiseless case is significantly reduced when bang-bang pulses are applied, being scaled down approximately by the ratio of the bang-bang period and the typical flipping time of the bistable fluctuation. Our analysis gives not only the effect of bang-bang control on the variance of these deviations, but also their entire distribution. As a result, bang-bang control works as a high-pass filter on the spectrum of noise sources. This indicates how the influence of  $1/f$ -noise ubiquitous to the solid state world can be reduced.

#### v) decoherence during 2-qubit gate operations

Solid state quantum bits are promising candidates for the realization of a *scalable* quantum computer. However, they are usually strongly limited by decoherence due to the many extra degrees of freedom of a solid state system. We investigate a system of two solid state qubits that are coupled via a ZZ type of coupling. This kind of setup is typical for pseudospin solid-state quantum bits such as charge or flux systems. We evaluated decoherence properties and gate quality factors in the presence of a common and two uncorrelated baths coupling to Z, respectively. At low temperatures, uncorrelated baths do

degrade the gate quality more severely. In particular, we show that in the case of a common bath, optimum gate performance of a CPHASE gate can be reached at very low temperatures, because our type of coupling commutes with the coupling to the decoherence, which makes this type of coupling attractive as compared to previously studied proposals with YY-coupling. Although less pronounced, this advantage also applies to the CNOT gate.

Solid state qubits realized in superconducting circuits are potentially extremely scalable. However, strong decoherence may be transferred to the qubits by various elements of the circuits that couple individual qubits, particularly when coupling is implemented over long distances. We proposed an encoding that provides full protection against errors originating from these coupling elements, for a chain of superconducting qubits with a nearest neighbor anisotropic XY-interaction. The encoding is also seen to provide partial protection against errors deriving from general electronic noise.

We examined the decoherence of an asymmetric two-qubit system that is coupled via a tunable interaction term to a common bath or two individual baths of harmonic oscillators. The dissipative dynamics are evaluated using the Bloch-Redfield formalism. It is shown that the behaviour of the decoherence effects is affected mostly by different symmetries between the qubit operator which is coupled to the environment and temperature, whereas the differences between the two bath configurations are very small. Moreover, it is elaborated that small imperfections of the qubit parameters do not lead to a drastic enhancement of the decoherence rates.

Quantum optimal control theory is applied to two and three coupled Josephson charge qubits. By using shaped pulses a CNOT gate can be obtained with a trace fidelity  $> 0.99999$  for the two qubits, and even when including higher charge states, the leakage is below 1%. Yet, the required time is only a fifth of the pioneering experiment [T. Yamamoto et al., Nature 425 (2003), 941] for otherwise identical parameters. The controls have palindromic smooth time courses representable by superpositions of a few harmonics. We outlined schemes to generate these shaped pulses such as simple network synthesis. The approach is easy to generalise to larger systems as shown by a fast realisation of TOFFOLI's gate in three linearly coupled charge qubits. Thus it is to be anticipated that this method will find wide application in coherent quantum control of systems with finite degrees of freedom whose dynamics are Lie-algebraically closed.

#### vi) Transfer of knowledge to quantum dot charge qubits

We studied electron transport through a system of two lateral quantum dots coupled in series. We considered the case of weak coupling to the leads and a bias point in the Coulomb blockade. After a generalized Schrieffer-Wolf transformation, cotunneling through this system is described using methods from lowest-order perturbation theory. We studied the system for arbitrary bias voltages below the Coulomb energy. We observed a rich, non-monotonic behavior of the stationary current depending on the internal degrees of freedom. In particular, it turns out that at fixed transport voltage, the current through the system is largest at weak-to-intermediate inter-dot coupling.

We analyze the decoherence of charge states in double quantum dots due to cotunneling. The system is treated using the Bloch-Redfield generalized master equation for the Schrieffer-Wolff transformed Hamiltonian. Decoherence, characterized through a relaxation  $T_1$  and a dephasing time  $T_2$ , can be controlled through the external voltage. The optimum point, where these times are maximum, is not necessarily in equilibrium. We outline the mechanism of this nonequilibrium-induced enhancement of lifetime and coherence. We discuss the relevance of our results for recent charge qubit experiments.

Recent experiments by [Hayashi et al., Phys. Rev. Lett. 91, 226804 (2003)] demonstrate coherent oscillations of a charge quantum bit in laterally defined quantum dots. We studied the intrinsic electron-phonon decoherence and gate performance for the next step: a system of two coupled charge qubits. The effective decoherence model contains properties of local as well as collective decoherence. Decoherence channels can be classified by their multipole moments, which leads to different low-energy spectra. It is shown that due to the super-Ohmic spectrum, the gate quality is limited by the single-qubit Hadamard gates. It can be significantly improved, by using double dots with weak tunnel coupling.

We performed a nonperturbative analysis of a charge qubit in a double quantum dot structure coupled to its detector. We show that strong detector-dot interaction tends to slow down and halt coherent oscillations. The transitions to a classical and a low-temperature quantum overdamping (Zeno) regime are studied. In the latter, the physics of the dissipative phase transition competes with the effective shot noise.

## **Publications and technical reports**

(a)

Engineering decoherence in Josephson persistent-current qubits  
C.H. van der Wal, F.K. Wilhelm, C.J.P.M. Harmans, and J.E. Mooij, Eur. Phys. J. B **31**, 111 (2003).

Nonlinear cotunneling through an artificial molecule  
U. Hartmann and F.K. Wilhelm, Phys. Rev. B **67**, 161307(R) (2003).

Decoherence and gate performance of coupled solid state qubits  
M.J. Storcz and F.K. Wilhelm, Phys. Rev. A **67**, 042319 (2003).

Theoretical analysis of continuously driven dissipative solid state qubits  
M.C. Goorden and F.K. Wilhelm, Phys. Rev. B **68**, 012508(R) (2003),

Asymptotic von Neumann measurement strategy for solid-state qubits  
F.K. Wilhelm, Phys. Rev. B **68**, 060503R (2003).

Design of realistic switches for coupling superconducting solid-state qubits  
M.J. Storcz and F.K. Wilhelm, Appl. Phys. Lett. **83**, 2389 (2003).

Nonequilibrium stabilization of charge states in double quantum dots  
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The spin-boson model with a structured bath: A comparison of approaches  
F.K. Wilhelm, S. Kleff, and J. von Delft, Chemical Physics **296**, 345 (2004).

Bang-bang refocusing of a qubit exposed to telegraph noise  
H. Gutmann, F.K. Wilhelm, W.M. Kaminsky and S. Lloyd, Quantum Information Processing **3**, 247 (2004).

Entangling flux qubits with a bipolar dynamic inductance  
B. L. T. Plourde, J. Zhang, K. B. Whaley, F. K. Wilhelm, T. L. Robertson, T. Hime, S. Linzen, P. A. Reichardt, C.-E. Wu, John Clarke, Phys. Rev. B **70**, 140501(R), 2004.

Measuring Non-Gaussian Fluctuations through Incoherent Cooper-Pair Current  
Tero T. Heikkilä, Pauli Virtanen, Göran Johansson, and Frank K. Wilhelm, Phys. Rev. Lett. **93**, 247005 (2004).

Full protection of superconducting qubit systems from coupling errors  
M.J. Storcz, J. Vala, K.R. Brown, J. Kempe, F.K. Wilhelm, and K.B. Whaley, Phys. Rev. B **72**, 064511 (2005).

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readout of flux qubits  
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Compensation of decoherence from telegraph noise by means of an open loop quantum-control technique  
H. Gutmann, W. M. Kaminsky, Seth Lloyd and Frank K. Wilhelm, Phys. Rev. A **71**, 020302 (2005) cond-mat/0308107

Intrinsic phonon decoherence and quantum gates in coupled lateral quantum dot charge qubits  
M.J. Storcz, U. Hartmann, S. Kohler, F.K. Wilhelm, Phys. Rev. B **72**, 235321 (2005).

Decoherence of a two-qubit system with a variable bath coupling operator  
M.J. Storcz, F. Hellmann, C. Hrlescu, F.K. Wilhelm, Phys. Rev. A **72**, 052314 (2005)

Ohmic and step noise from a single defect center hybridized with a Fermi sea  
R. de Sousa, K.B. Whaley, F.K. Wilhelm, and J. von Delft, Phys. Rev. Lett. **95**, 247006 (2005).

(b)

Decoherence of charge states in double quantum dots due to cotunneling  
Udo Hartmann and Frank K. Wilhelm, Physica Status Solid (b) **233**, 385 (2002).

Engineering the quantum measurement process for the persistent current qubit  
T.P. Orlando, L. Tian, D.S. Crankshaw, S. Lloyd, C.H. van der Wal, J.E. Mooij, and F.K. Wilhelm, Physica C **368**, 294 (2002).



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Decoherence of flux qubits coupled to electronic circuits  
F.K. Wilhelm, M.J. Storcz, C.H. van der Wal, C.J.P.M. Harmans, and J.E. Mooij, *Adv. Solid State Phys.* **43**, 763 (2003)

(c)

Read-out and control of superconducting flux qubits and similar systems  
Invited paper presented at the international workshop “Quantum Computers: Mesoscopic implementations, perspectives and open problems (Quiproquo 2002)”, Torino (I), 10.-21.6.02

Realistic theory of solid-state quantum bits  
presentation at the QCPR '02, quantum computing progress review, Nashville, TN

Decoherence of charge states in double quantum dots due to cotunneling (Udo Hartmann)  
Decoherence of coupled solid state qubits, (Markus Storcz)  
Superconducting quantum bits: Control, coherence, and read-out (Frank K. Wilhelm)  
CeNS-Workshop “Recent Highlights in the Nanoworld”, Wildbad-Kreuth, Germany, Oct. 6-9, 2002

Coupled flux qubits: Dynamics, decoherence, performance, and switches  
SQUBIT-meeting, Paris, December 2002

Quantum control and decoherence in small superconducting circuits  
Invited talk in focus session, DPG Frühjahrstagung (Spring Meeting of the German Physical Society), Dresden (D), March 2003.

Engineering decoherence using statistical physics and quantum information theory  
Workshop THINQC, Theory in quantum computing, Harper's Ferry, WV, June 2003

Open systems in statistical physics and quantum information Lorentz workshop “Hot topics in quantum statistical physics”, Leiden (NL), 8/2003, invited talk.

Decoherence and gate performance of coupled solid state qubits M.J. Storcz and F.K. Wilhelm, Lorentz workshop “Hot topics ...”, Leiden (NL), 8/2003, poster.

Compensation of decoherence from telegraph noise by means of bang-bang control H. Gutmann and F.K. Wilhelm, Lorentz workshop “Hot topics ...”, Leiden (NL), 8/2003, poster.

Realistic theory of solid-state qubits Quantum computing program review (QCPR 2003), Nashville, TN, 8/2003.

Theory for quantum dot charge qubits – decoherence due to cotunneling U. Hartmann and F.K. Wilhelm, Quantum computing program review (QCPR 2003), Nashville, TN, 8/2003.

Engineering decoherence of superconducting qubit SQUBIT meeting, Pisa (I), 9/2003.

Engineering decoherence of solid-state qubits CeNS workshop “Transport in

nanosystems", Seeon (D), 9/2003.

Decoherence and gate performance of coupled solid state qubits M.J. Storcz and F.K. Wilhelm, CeNS workshop "Transport in nanosystems", Seeon (D), 9/2003, poster.

Theory for quantum dot charge qubits – decoherence due to cotunneling U. Hartmann and F.K. Wilhelm, CeNS workshop "Transport in nanosystems", Seeon (D), 9/2003, poster.

Compensation of telegraph noise decoherence by means of bang-bang control H. Gutmann and F.K. Wilhelm, CeNS workshop "Transport in nanosystems", Seeon (D), 9/2003, poster.

Engineering decoherence of superconducting qubit Kryo 2003 workshop, Blaubeuren (D), 9/2003.

Decoherence from telegraph noise and its dynamical compensation  
Conference Solid State Quantum Information Processing (SSQIP), Amsterdam, Dec. 2004

*Decoherence without  $T_2$*

*Enhancing the Gate Performance of Superconducting Qubits*

*Compensation of telegraph noise decoherence by means of bang-bang control*

Spring meeting of the German Physical Society, Regensburg, March 2004.

Workshop "Are the DiVincenzo Criteria fulfilled in 2004?", Osaka (JP), 5/2004:  
"Superconducting qubits (theory)" and "Alternatives to the standard paradigm"  
Invited talks

Processing of Quantum Information in RSFQ Circuits and Qubits, Bad Honnef (D), 11/2004, "Finding optimum pulses for quantum logic gates"

Quantum Information Processing 2004, Herrsching (D), 9/2004, "Optimum control of superconducting qubits", Invited talk

Feynman Festival, College Park, MD (USA), 8/2004, "Decoherence and gate quality of coupled flux qubits"  
Invited talk

Quantum computing program review (QCPR), Orlando, FL (USA), 8/2004, "Realistic theory of solid-state qubits"

NATO-ASI "Manipulating quantum coherence in condensed matter", Cluj-Napoca (RO), 8-9/2005,

"Superconducting quantum devices", "Decoherence I: Mostly weak coupling",

"Decoherence II: Strong

coupling and non-Markovian effects", "From one to two qubits" invited lectures

Quantum computing program review (QCPR), Tampa, FL (USA), 8/2005, "Realistic theory of solid-state qubits"

Workshop "Paris spring meeting on superconducting qubits, 5/2005 "Coherence and control of coupled qubit, systems", invited talk

DPG Spring meeting Berlin (D), 3/2005 "Optimum pulses for quantum logic gates", invited talk in Symposium

(d)

Reduced visibility of quantum oscillations in the spin boson model  
Frank K. Wilhelm, cond-mat/0507526

Efficient readout of flux qubits at degeneracy  
A. Käck and F.K. Wilhelm, cond-mat/0505537

Strong coupling of a qubit to shot noise  
U. Hartmann and F.K. Wilhelm, cond-mat/0505132

Optimal Control of Coupled Josephson Qubits  
A.K. Spörl, T. Schulte-Herbrüggen, S.J. Glaser, V. Bergholm, M.J. Storcz, J. Ferber, F.K. Wilhelm, quant-ph/0504202

(e)

Interim Progress Report 1, July 19, 2002  
Interim Progress Report 2, October 18, 2002  
Interim Progress Report 3, February 1, 2003  
Interim Progress Report 4, May 15, 2003  
Interim Progress Report 5, July 31, 2003  
Interim Progress Report 6, October 10, 2003  
Interim Progress Report 7, January 31, 2004  
Interim Progress Report 8, April 30, 2004  
Interim Progress Report 9, Dec 31, 2004  
Interim Progress Report 10, Sept 30, 2005  
final report, Dec 31, 2005

## **Personnel**

Dr. Frank K. Wilhelm, earned Habilitation (formal German teaching degree), 2004  
Dr. Henryk Guttman, earned PhD, 2005  
Dr. Udo Hartmann, earned PhD, 2005  
Dr. Markus Storcz, earned PhD, 2005

Dr. Gutmann was funded through ARO when he obtained his PhD. Drs. Wilhelm, Hartmann, and Storcz contributed to the ARO program when earning their degrees, but were not funded.

## **Inventions**

No patents were filed or attempted as a part of this project